OITS 628
June 1997

arXiv:nucl-th/9706062v1 24 Jun 1997

Enhanced J/ψ Suppression Due to Gluon Depletion

Rudolph C. Hwa[1], **Ján Pišút**[2] **and Neva Pišútová**[2]

[1]Institute of Theoretical Science and Department of Physics
University of Oregon, Eugene, OR 97403-5203, USA

[2]Department of Physics, Comenius University, SK-84215, Bratislava, Slovakia

Abstract

The nonlinear effect of gluon depletion in the collision of large nuclei can be large. It is due to multiple scatterings among comoving partons initiated by primary scattering of partons in the colliding nuclei. The effect can give rise to substantial suppression of J/ψ production in very large nuclei, even if the linear depletion effect is insignificant for the collisions of nuclei of smaller sizes. This mechanism offers a natural explanation of the enhanced suppression in the Pb-Pb data recently observed by NA50.

In a previous paper [1] we have examined the issues involved in ascribing some aspect of the phenomenon of J/ψ suppression in heavy-ion collisions [2] to the depletion of gluons prior to the hard subprocess of $c\bar{c}$ production. What we have found is that the data on the survival probability S without the points from Pb-Pb collisions [3, 4], by themselves, cannot distinguish whether the suppression is due to gluon depletion or hadronic-nuclear absorption. That is, both mechanisms contribute to an exponential dependence of S on the effective path length L (or on $\log AB$). We now consider the enhanced suppression in the Pb-Pb data of NA50 [4] and show how gluon depletion can naturally account for it. Furthermore, it is possible for that to happen even if the "normal" suppression in the lighter-ion data is due mainly to the absorption mechanism with negligible depletion effect.

Many suggestions have been advanced to account for the enhancement of J/ψ suppression observed in the Pb-Pb collision data [5]-[11]. They all refer to the absorption processes after the production of the $c\bar{c}$ state. Our suggestion is concerned with the depletion of gluons before the $gg \to c\bar{c}$ subprocess. The basic idea is rather intuitive and can be described qualitatively before we go into the details. Consider a row of nucleons in nucleus A colliding with another row in nucleus B, and suppose that the n_Ath one from the front of the former (call it a) collides with the n_Bth one in the latter (call it b) in a hard process creating $c\bar{c}$. The gluon depletion mechanism discussed in [1] takes into account of the loss of gluons in a (due primarily to $g \to q\bar{q}$) as it goes through B until $gg \to c\bar{c}$ occurs with a gluon in b; similarly, the gluons in b are depleted as b traverses A. We shall refer to this process as linear depletion for reasons that will become clear below. What we now want to emphasize is that a nonlinear depletion process may be even more important. Such a process is due to the

interaction of the gluons in a with the slower partons liberated from the $n_A - 1$ forerunners in A broken by earlier interactions, and likewise b with the partons of the $n_B - 1$ forerunners in B. In an imperfect, yet helpful, analogy one may think of a multicar accident on a busy, foggy highway and recognize that most of the collisions are between cars originally going in the same direction.

Let us first summarize the essence of the linear effect considered in [1]. Our notation will follow that of [1], but abbreviated. The probability that a nucleon in A makes ν_1 collisions in B before the hard subprocess is

$$\pi_{\nu_1} = \frac{1}{\nu_1!} {n_B}^{\nu_1} e^{-n_B} \quad , \qquad n_B = \sigma_{\text{in}} T_B^- \quad , \tag{1}$$

where T_B^- is the path length that is traversed in B before the $c\bar{c}$ production and is dependent on the impact parameter b_B and longitudinal position z_B, both being suppressed. If the depletion factor per collision at fixed momentum fractions x_1 and x_2 is D ($D = 1$ for no depletion), then the suppression factor at fixed b and z in A and B is

$$\Gamma_{AB}^{(d)} = \sum_{\nu_1, \nu_2} \pi_{\nu_1} \pi_{\nu_2} D^{\nu_1 + \nu_2} = \exp\left[-(1-D)(n_A + n_B)\right] \quad , \tag{2}$$

where π_{ν_2} is defined as in (1), but with B replaced by A. It is the simple sum, $n_A + n_B$, in (2) that leads us to call the effect linear. The exponential behavior of $\Gamma_{AB}^{(d)}$ is what generates, after integration over b and z, the approximate exponential dependence of S on L that is indistinguishable from the Gerschel-Hüfner formula [12], derived from purely absorptive consideration.

The nonlinear effect that we now describe arises from the interactions with the forerunners. At the partonic level the linear effect is due to the primary interactions of gluons in nucleons going in opposite directions, while the nonlinear effect is due to the secondary, tertiary, etc. interactions among partons moving in the same direction, initiated by primary interactions. The rapidity separation, Δy, between the participants of the primary interaction is large because they belong to the nuclei A and B separately. On the other hand, Δy between the partons involved in the secondary (or tertiary, etc.) interactions is small because they belong to the same nucleus. Ordinarily, in an unperturbed nucleus or in deep inelastic scattering of a nucleus, those partons in different nucleons do not interact except in the context of nuclear binding and shadowing. However, if a primary interaction has taken place between two colliding nuclei, the scattered parton in A, whether at large or small angle, can interact with a parton coming from behind in the same or neighboring rows. Since they are comovers, their interaction can be much stronger than the primary interaction, a property that is consistent with the general notion of strong interaction in soft processes being short-ranged (in rapidity). Thus even if the linear depletion effect is small, the nonlinear effect need not be.

If we consider an $n_A \times n_B$ matrix, representing the possible pairings of n_A and n_B nucleons in collisions, the last row and last column contribute to the linear depletion effect. [Their sum $n_A + n_B - 1$ appears as $n_A + n_B$ in (2) in compensation for the fact that the first collision of a nucleon with a row of nucleons is the normal pp collision, whose cross section is larger than those of the subsequent collisions that involve the broken nucleon propagating

downstream. To elaborate on this point is too much of a digression that is not germane to the following discussion.] The remaining part of the matrix having $(n_A - 1)(n_B - 1)$ pairings contributes to the quadratic depletion effect due to multiple parton scatterings. Let us define

$$n'_A = (n_A - 1)\ \Theta(n_A - 1) \quad , \tag{3}$$

and similarly for n'_B. Then, assuming $A \le B$, the average number of collisions that the forerunners of a in A make with the forerunners of b in B, producing comoving partons that can interact with the partons of a, is $n'_A n'_B - {n'_A}^2/2$; that for producing comoving partons with the ones in b is ${n'_A}^2/2$. This way of partitioning the $n'_A n'_B$ pairings can be visualized in the forward light-cone of AB collision, where the former lie on the A side of the interaction region, while the latter lie on the B side. The precise method of partitioning is unimportant, as will become evident presently.

The probabilities that a and b can interact ν'_1 and ν'_2 times with their respective forerunners are

$$\pi'_{\nu'_1} = \frac{1}{\nu'_1!}\ (n'_A n'_B - {n'_A}^2/2)^{\nu'_1}\ e^{-(n'_A n'_B - {n'_A}^2/2)} \quad , \tag{4}$$

$$\pi'_{\nu'_2} = \frac{1}{\nu'_2!}\ ({n'_A}^2/2)^{\nu'_2}\ e^{-{n'_A}^2/2} \quad . \tag{5}$$

If D' is the effective gluon depletion factor for each of those interactions, then the corresponding suppression factor, analogous to (2), is

$$\Gamma'^{(d)}_{AB} = \sum_{\nu'_1, \nu'_2} \pi'_{\nu'_1} \pi'_{\nu'_2}\ D'^{\nu'_1 + \nu'_2} = \exp\left[-(1 - D')\ n'_A\, n'_B\right] \quad . \tag{6}$$

We refer to this as the quadratic depletion effect, since it is $n'_A n'_B$ that appears in the exponent, as opposed to $n_A + n_B$ in (2). As it is in (2), the dependences on b_A, z_A, b_B, and z_B have been suppressed in (6).

The combined suppression factor due to both linear and quadratic depletion as well as absorption [1] is now

$$P = \exp\left[-(1 - D)\,(n_A + n_B) - (1 - D')\, n'_A n'_B - \sigma_a (T^+_A + T^+_B)\right] \quad , \tag{7}$$

where σ_a is the absorption cross section and T^+_A is the path length in A traversed by the J/ψ system. Exhibiting the b and z dependences, we have [1]

$$T^\pm_A = (1 - \frac{1}{A})\ \rho_0\ (L_A \pm z_A) \quad , \qquad L_A = (R_A^2 - s^2)^{1/2} \quad , \tag{8}$$

and similarly for $T^\pm_B$, with $\vec{b}_A = \vec{s}$ and $\vec{b}_B = \vec{b} - \vec{s}$. The average overall suppression factor (more precisely, survival probability) is

$$S^{AB}_{J/\psi} = N^{-1}_{AB} \int d^2 b \int d^2 s \int_{-L_A}^{L_A} dz_A \int_{-L_B}^{L_B} dz_B\ P \quad , \tag{9}$$

where N_{AB} is the same integral as in (9) but with P replaced by 1.

To see how $S^{AB}_{J/\psi}$ depends on A and B, let us examine the parameters in the formula. Without the quadratic depletion terms in (7), we have

$$P_1 \equiv P(D' = 1) = \exp\left[-\sigma_d\ (T_A^- + T_B^-) - \sigma_a\ (T_A^+ + T_B^+)\right] \quad , \tag{10}$$

where $\sigma_d = \sigma_{\rm in}(1 - D)$. As pointed out in [1], (10) exhibits the symmetry between the depletion effect before the formation of J/ψ and the absorption effect afterwards. That is why the exponential dependence of the empirical $S^{AB}_{J/\psi}$ on the effective length L (or $\log AB$) cannot distinguish the two effects. So long as the combined cross section $\sigma_c = \sigma_a + \sigma_d$ is around 7 mb, the heavy-ion data, excluding the Pb-Pb collisions, can be fitted by any ratio $\eta = \sigma_d/\sigma_a$. Now, we consider the contribution from the quadratic depletion term in (7) only, giving

$$P_2 \equiv P(D = 1, \sigma_a = 0) = \exp\left[-\ \tau\ (n_A - 1)\,(n_B - 1)\,\Theta(n_A - 1)\,\Theta(n_B - 1)\right] \tag{11}$$

where $\tau = 1 - D'$, a parametrization, like σ_d, having the more proper sense of depletion in that $\tau = 0$ means no depletion. There are a number of features of (11) worth noting.
(a) While the discussions in the introduction and in the paragraph containing (3) regard n_A and n_B as integers for the sake of ease in describing the nonlinear depletion mechanism, they can in reality have any positive value by virtue of their definitions, $n_{A,B} = \sigma_{\rm in} T^-_{A,B}$. That is why the step functions in (3) and (11) are important to ensure that the participants of the process, n'_A and n'_B, are nonnegative. As a consequence there is a threshold effect, i.e., A and B must be large enough for the mechanism to be operative.
(b) The inelastic cross section $\sigma_{\rm in}$ is relevant in the determination of the position of the threshold. It is not the $\sigma^{pp}_{\rm in}$ for pp collision because, except for the first collisions on the front sides of the nuclei, most of the collisions are between broken nucleons [13], which consist mainly of the parton fluxes that propagate downstream after the bound nucleons are broken by the first collisions. $\sigma_{\rm in}$ is an effective cross section for the collision of such broken nucleons, and there exist no reliable estimates for its value. Using p' to denote broken nucleon, and taking $\sigma^{pp}_{\rm in} \approx 30$ mb, it is not unreasonable to consider $\sigma^{p'p}_{\rm in} \approx$ 20-25 mb, and $\sigma^{p'p'}_{\rm in} \approx (\sigma^{p'p}_{\rm in})^2/\sigma^{pp}_{\rm in} \approx$ 13-21 mb. We shall adopt $\sigma_{\rm in} \approx$ 15-25 mb as typical values.
(c) The quadratic depletion parameter τ can be substantially different from zero, even if the linear effect measured by σ_d is zero, since, as discussed earlier, the interaction between partons with small rapidity separation can be much greater than that between partons with large Δy. Since the determination of τ from first principles is difficult, we shall use it as a free parameter in the following. It should be noted that even if $D' = 0$, i.e., total depletion per collision, τ attains its maximum value 1, so (11) does not give $P_2 = 0$. That is because the Poissonian fluctuations in (4) and (5) allow for $\nu'_1 = \nu'_2 = 0$, which result in a nonvanishing probability for the passage of the gluon fluxes with minimal influence by the depletion mechanism.

To gain some further insight in the quadratic depletion effect, let us compute $S^{AB}_{J/\psi}$, taking only P_2 into account, i.e., by substituting (11) alone into (9). Using the integration procedure developed in [1], we obtain the results shown in Fig. 1, where $\sigma_{\rm in}$ is set at 15, 20 and 25 mb; the shaded regions are bounded by $\tau = 0.5$ from above (for illustrative purpose) and $\tau = 1.0$ from below. Evidently, the threshold for the quadratic depletion effect is higher

at smaller $\sigma_{\rm in}$, since there would be less participants for the multiscattering subprocesses unless A is higher. Furthermore, even at maximum depletion ($\tau = 1$) there is still a residual rate of J/ψ production because of the aforementioned probability of gluon passage without depletion. We note that, although the parameters $\sigma_{\rm in}$ and τ are not empirically familiar, their values used in Fig. 1 are sensible estimates, so the suppression effect revealed is a natural consequence of a physical process that is not contrived to explain the data.

For a comparison with the data [3, 4] we include both P_1 and P_2 in (9) and calculate the overall suppression factor. Since, as found in [1], the combined effect of absorption and linear depletion is insensitive to the ratio $\eta = \sigma_d/\sigma_a$, we choose the uncontroversial values: $\sigma_c = \sigma_a + \sigma_d = 7$ mb, and $\eta \approx 0.1$. For quadratic depletion effect we use $\sigma_{\rm in} = 20$ mb and $\tau = 0.5$-1.0. The result is shown by the triangles in Fig. 2. The agreement with the data [4] is evidently very good. Of course, if there exists enhanced nuclear, hadronic or plasma absorption at high AB, it can be accommodated by reducing the value of τ. What is shown here is that the quadratic gluon depletion effect by itself is able to account for the enhanced suppression in the Pb-Pb data.

A concomitant phenomenon associated with quadratic gluon depletion is the suppression of back-to-back $D\bar{D}$ production in Pb-Pb collision, but not in AB collisions where A is smaller. Photon production would not necessarily be suppressed, since the quarks produced by gluon conversion can carry on the γ-producing subprocess without inhibition. Dilepton production may or may not be enhanced, depending on whether the extra quarks and antiquarks are produced inside or outside the interaction region. It is therefore important that all those signatures should be examined experimentally in the collisions of very heavy ions.

Whether or not the nonlinear gluon depletion process can wholly or partially account for the enhanced J/ψ suppression phenomenon, what we have discovered here is that there is a whole class of parton interactions whose role in heavy-ion collisions has hitherto been overlooked, but they are of crucial importance to any process whose rate depends on the magnitude of the gluon flux available in large nuclei.

This work was supported, in part, by the U.S.-Slovakia Science and Technology Program, National Science Foundation under Grant No. INT-9319091 and by the U. S. Department of Energy under Grant No. DE-FG03-96ER40972.

References

[1] R. C. Hwa, J. Pišút, and N. Pišútová, OITS-621 (nucl-th/9702051), to be published in Phys. Rev. C.

[2] For a review see H. Satz, and J.-P. Blaizot and J.-Y. Ollitrault in *Quark-Gluon Plasma*, edited by R.C. Hwa (World Scientific, Singapore, 1990), and D. Kharzeev and H. Satz in *Quark-Gluon Plasma 2*, edited by R.C. Hwa (World Scientific, Singapore, 1995).

[3] C. Lourenço, Nucl. Phys. **A610**, 552c (1996).

[4] M. Gonin *et al.*, (NA50), Nucl. Phys. **A610**, 404c (1996).

[5] D. Kharzeev, C. Lourenço, M. Nardi, and H. Satz, Z. Phys. C **74**, 307 (1997).

[6] J.-P. Blaizot and J.-Y. Ollitrault, Phys. Rev. Lett. **77**, 1703 (1996).

[7] S. Gavin and R. Vogt, Nucl. Phys. **A610**, 442c (1996); Phys. Rev. Lett. **78**, 1006 (1997).

[8] A. Capella, A. Kaidalov, A. Kouidu Akil, and C. Gerschel, Phys. Lett. **B393**, 431 (1997).

[9] J. Ftáčnik, J. Pišút, and N. Pišútová, hep-ph/9604304.

[10] W. Cassing and C. M. Ko, Phys. Lett. **B396**, 39 (1997).

[11] C. Y. Wong, Phys. Rev. C **55**, 2621 (1997); Phys. Rev. Lett. **76**, 196 (1996).

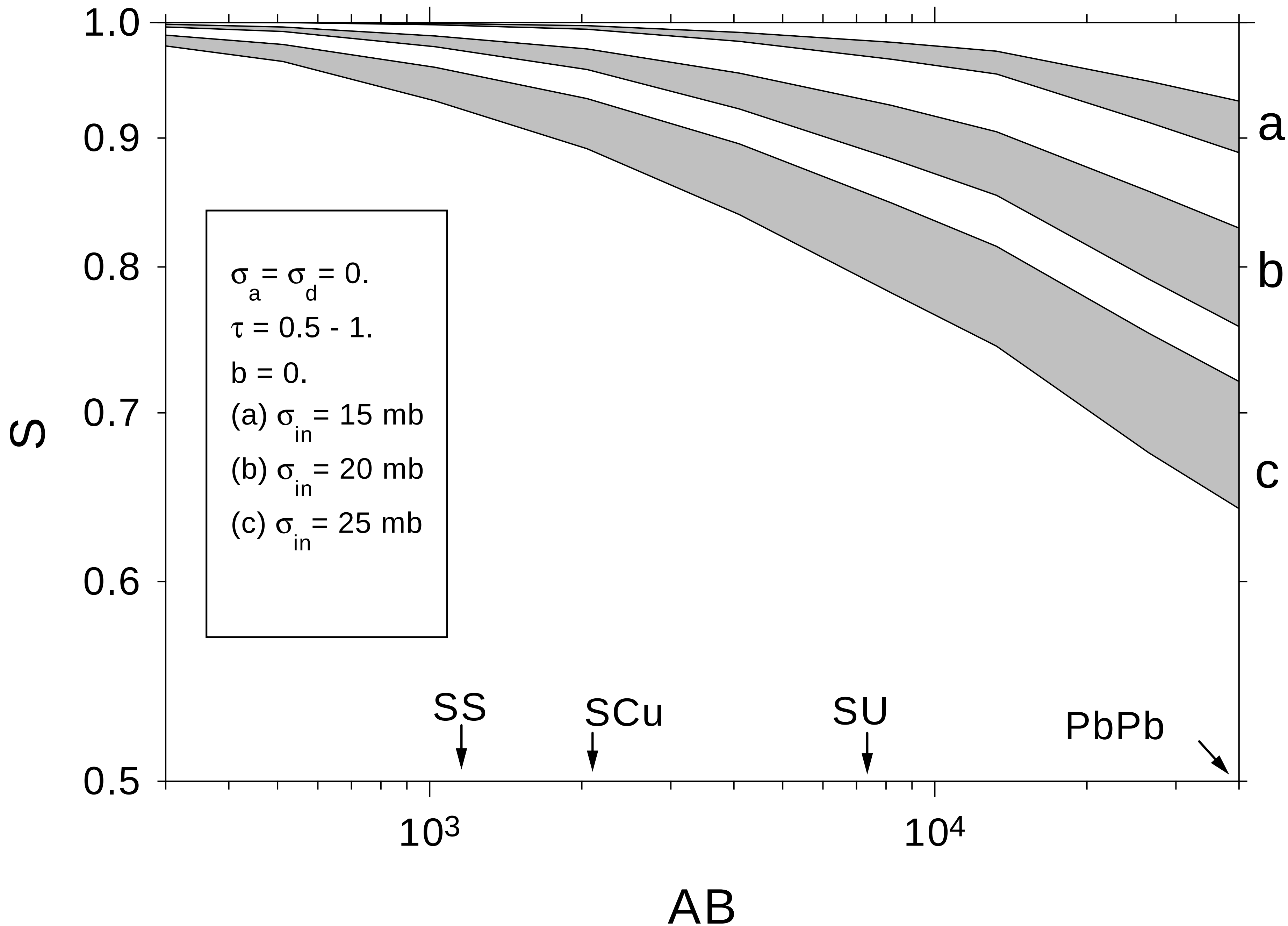
[12] C. Gerschel and J. Hüfner, Phys. Lett. B **207**, 253 (1988); Z. Phys. C **56**, 171 (1992).

[13] R. C. Hwa and X. -N. Wang, Phys. Rev. D **39**, 2561 (1989).

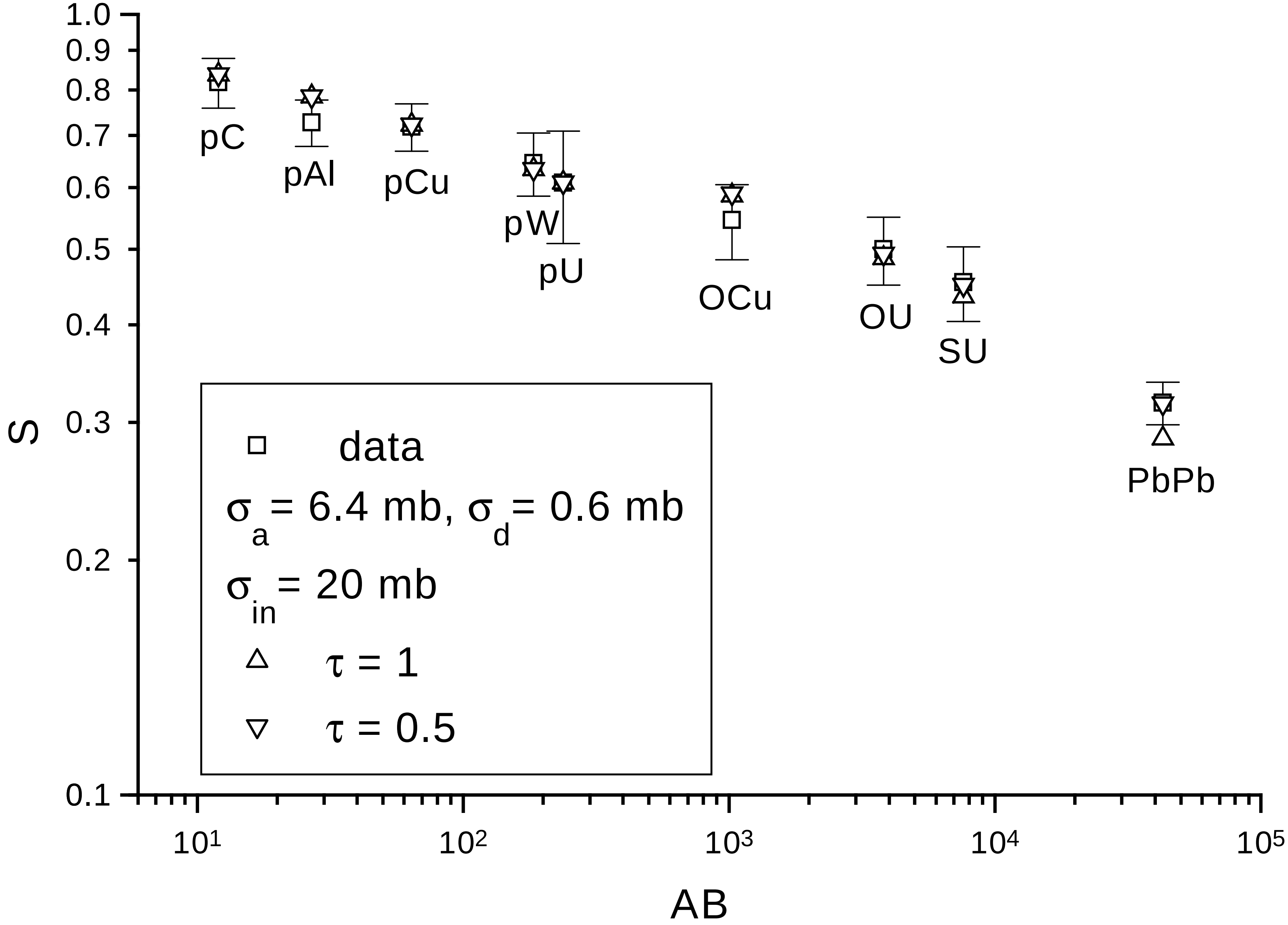
Figure Captions

Fig. 1 The suppression factor $S_{J/\psi}^{AB}$, abbreviated as S, is plotted against AB, when only the quadratic depletion effect is taken into account. The shaded regions are for τ having values between 0.5 (upper boundaries) and 1.0 (lower boundaries). Three values of σ_{in} are used, as indicated.

Fig. 2 The suppression factor $S_{J/\psi}^{AB}$, abbreviated as S, is plotted against AB, when both the usual linear (mainly absorption) effect and the quadratic depletion effect are taken into account. The data are from [4]. Typical values for the parameters in the theoretical calculations have been used.



1.0
0.9
0.8
0.7
0.6
0.5
S
$\sigma_a = \sigma_d = 0.$
$\tau = 0.5 - 1.$
b = 0.
(a) $\sigma_{in} = 15$ mb
(b) $\sigma_{in} = 20$ mb
(c) $\sigma_{in} = 25$ mb
a
b
c
SS
SCu
SU
PbPb
10^3
10^4
AB



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
S
pC
pAl
pCu
pW
pU
OCu
OU
SU
PbPb
data
σ_a = 6.4 mb, σ_d = 0.6 mb
σ_{in} = 20 mb
τ = 1
τ = 0.5
10^1
10^2
10^3
10^4
10^5
AB